

Further Developments in Modeling Creep-Effects Within Structural SiC/SiC Components

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Anticipating the implementation of advanced SiC/SiC composites into turbine section components of future aero-propulsion engines, the primary objective of this on-going study is to develop physics-based analytical and finite-element modeling tools to predict the effects of constituent creep on SiC/SiC component service life. A second objective is to understand how to possibly manipulate constituent materials and processes in order to minimize these effects. Focusing on SiC/SiC components experiencing through-thickness stress gradients (e.g., airfoil leading edge), prior NASA creep modeling studies showed that detrimental residual stress effects can develop globally within the component walls which can increase the risk of matrix cracking. These studies assumed that the SiC/SiC composites behaved as isotropic viscoelastic continuum materials with creep behavior that was linear and symmetric with stress and that the creep parameters could be obtained from creep data as experimentally measured in-plane in the fiber direction of advanced thin-walled 2D SiC/SiC panels. The present study expands on those prior efforts by including constituent behavior with non-linear stress dependencies in order to predict such key creep-related SiC/SiC properties as time-dependent matrix stress, constituent creep and content effects on composite creep rates and rupture times, and stresses on fiber and matrix during and after creep.



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Structural SiC/SiC Components***

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Background

Under the new NASA Fundamental Aeronautics Program, one of the objectives is to develop physics-based tools and concepts that will allow advanced SiC/SiC CMC systems to be implemented in turbine section of future supersonic engines.

Mechanistic modeling studies are now on-going at NASA Glenn

(1) to develop advanced design tools to down-select and improve the constituent materials, processes, and fiber architectures for SiC/SiC turbine components, and
(2) to develop advanced lifing tools that address the multiple service conditions of these components.



Key Concerns for Lifing of SiC/SiC Components

- Thermal Stability of the SiC/SiC constituents
- Service Stability of the Environmental Barrier Coating (EBC) required for long term life
- **Creep-Related Effects** within the SiC/SiC due to Temperature, Stress, and their Gradients
 - *Constituent Rupture*: As with monolithic ceramics, stress-induced creep implies flaw growth and time-dependent rupture of the matrix and fiber
 - *Internal Environmental Attack*: At stresses above matrix cracking, creep can increase crack openings, leading to enhanced internal attack of all constituents and shorter life
 - *Residual Stress Development*: At stresses below matrix cracking, creep can put matrix in more tension with time, resulting in greater risk of matrix cracking and reduction of component environmental life.

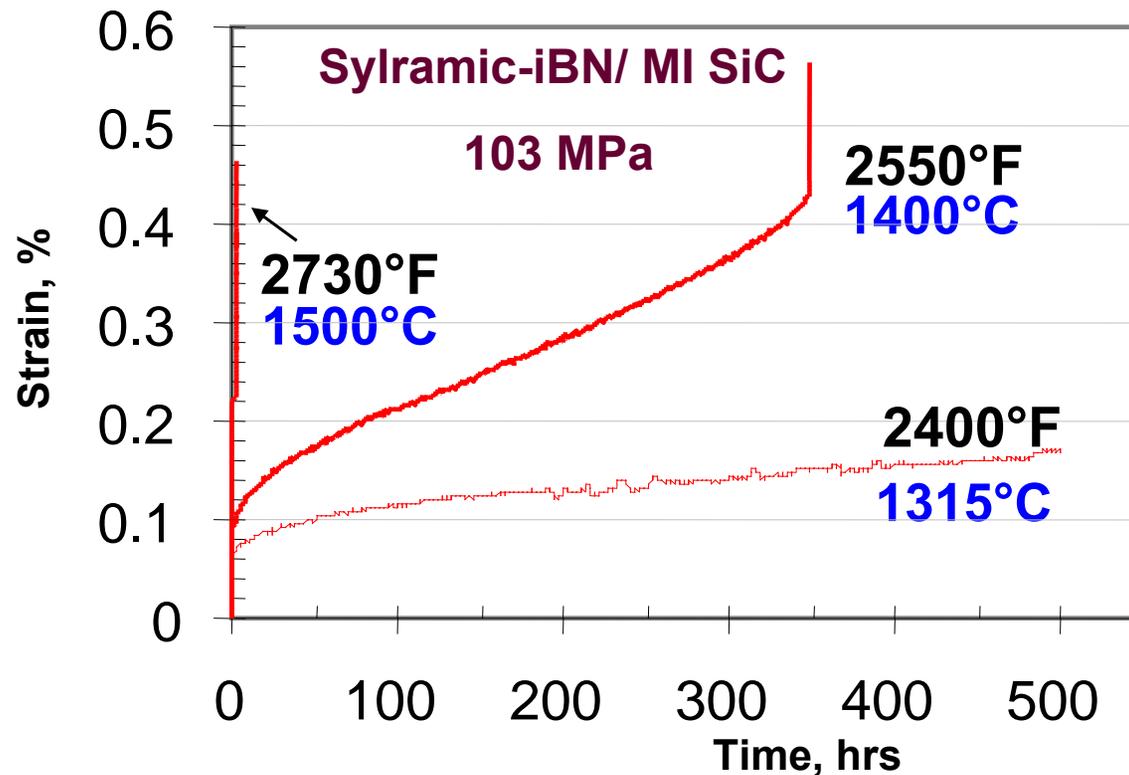


Objectives/Outline

- Briefly review previous NASA results related to the development of initial Analytical and Finite Element Models for the intrinsic creep of advanced SiC/SiC CMC materials at stresses below the onset of matrix cracking
- Present recent developments aimed at improving the creep models using more realistic constituent and physics-based mechanisms



**Typical Data for Initial Creep Model Development:
Constant Temperature, Constant Stress Results
for On-Axis Creep of Some Advanced
NASA-Developed 2D 0/90-balanced SiC/SiC Panels**



Composite data below matrix cracking shows elastic, primary, and steady-state secondary creep



Initial SiC/SiC Composite Creep Model

- Assume SiC/SiC composite is a **homogeneous isotropic material** with elastic, anelastic, and viscous (non-recoverable) strain components that are linear and symmetric with tension and compressive stresses

- **Analytical Model:** Total creep strain vs. time given by

$$e(t) / e(0) = 1 + A [1 - \exp(-t/\tau(T))] + A t/8\tau(T)$$

A = system-dependent creep parameter

τ = temperature-dependent constant

- **FE Model:** Stress Relaxation vs. time given by 4-parameter 2-term Prony Series

$$G(t)/G(0) = 0.30 \exp(-t/C) + 0.70 \exp(-t/D)$$

- Constants A, C, D, and τ can be empirically determined from on-axis creep data for advanced SiC/SiC systems from 1200 -1450°C at stresses below matrix cracking



Best-Fit Creep Parameter A for Some Advanced NASA-Developed SiC/SiC Systems

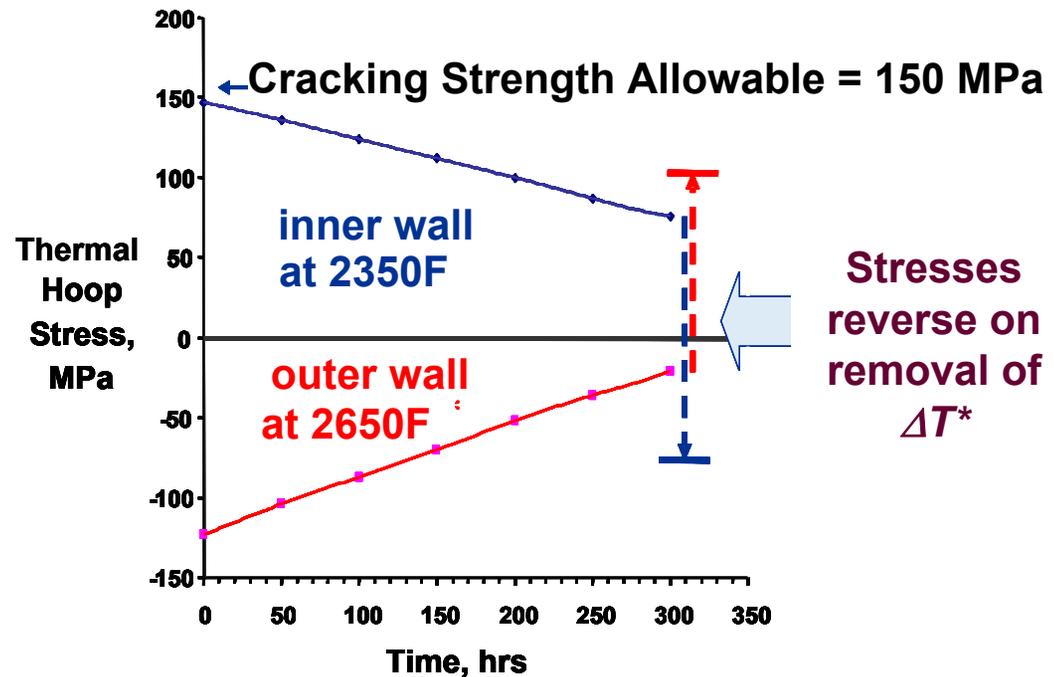
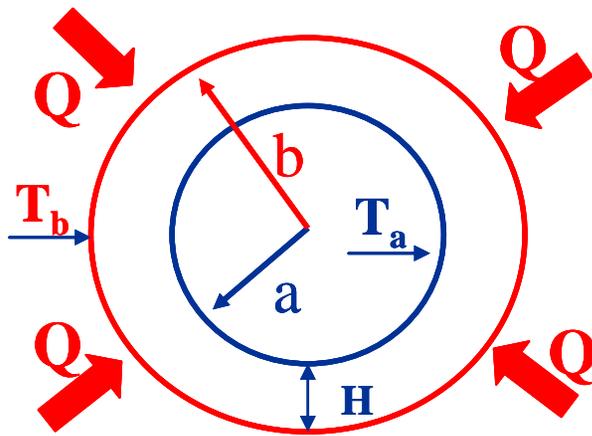
	NASA N22		NASA N24A		NASA N26
Upper Use Temperature	2200°F		2400°F		2600°F
SiC Fiber	Sylramic		Sylramic-iBN		Sylramic-iBN
Matrix 1	CVI SiC		CVI SiC		CVI SiC (anneal)
Matrix 2	Slurry SiC + Si		Slurry SiC + Si		PIP SiC (anneal)
Creep Parameter A	3.2		1.4		0.6
Current NASA Interest			Type 1		Type 2



Initial Creep Model Applied to Internally-Cooled Tube:

*Hoop Stress Relaxation for Type-2 SiC/SiC at $\Delta T^*_{max} = 300^\circ F$*

Tube Dimensions: $H/a = 0.33$



Both Inner and Outer Wall stresses relax with time, thereby increasing material reliability at temperature. But Outer Wall goes into tension on ΔT^* removal (e.g., during component cool-down). Outer wall residual tension adversely increases with time at temperature.



Recent Efforts Toward Improved Creep Models

Objective: Increase the fidelity of the initial creep models by developing physics- and constituent-based models for advanced SiC/SiC components so that the matrix stress can be monitored throughout component life in order to minimize risk of cracking and internal environmental attack

Key Needs:

- Although convenient, remove the assumption of linearity since much data exists that show the SiC fiber and matrix constituents display both primary and secondary creep strains that are non-linear with stress:
$$\mathbf{e} = \sigma / E + \sigma \alpha [1 - \exp(-t/\tau(T))] + \sigma^n \beta(T) t$$
 - constituent viscous-strain stress exponent **n** can be > 1
 - α, τ are the constituent anelastic parameters
 - $\beta = \beta_0 \exp(-B/T)$ are the constituent viscous parameters
- Develop approaches that measure the constituent creep parameters either directly from constituent creep measurements or indirectly from SiC/SiC creep data



Current Approaches for Determining Constituent Creep Parameters

SiC Fibers:

Using in-house tests and literature data measured on straight fibers and multi-fiber tows, NASA has determined the following best-fit creep parameters for two high-performance SiC fibers:

	E_f	n_f	α_f	β_{fo}	B_f
Hi-Nicalon-S	350 GPA	3	0.6	$8 \times 10^6 \text{ MPA}^{-1/3}$	86000 K
Sylramic-iBN	350 GPA	3	0.6	$13 \times 10^6 \text{ MPA}^{-1/3}$	86000 K

SiC Matrices:

Since high-performance SiC matrices typically have complex microstructures that are not reproducible as monolithics, best-fit matrix creep parameters were determined using composite creep theory, known fiber creep parameters, and data from constant stress creep tests on relevant composites.



Method for Determining Matrix Viscous Creep Parameters

- For a given SiC/SiC on-axis creep curve at constant stress σ_c below matrix cracking, assume fiber, matrix, and composite creep strain and creep rates are the same at any given time
- Assume when a steady-state creep rate $\dot{\epsilon}_{ss}$ is reached, the fiber and matrix have reached their equilibrium stresses, so that the **Fiber Stress at Steady State $\sigma_f(\infty)$** can be determined from NASA-measured viscous parameters n_f and β_f for the fiber:

$$\sigma_f(\infty)^{n_f} = \dot{\epsilon}_{ss} / \beta_f$$

- **Matrix Stress at Steady State $\sigma_m(\infty)$** can then be calculated from

$$\sigma_m(\infty) = [\sigma_c - V_f \sigma_f(\infty)] / V_m$$

and β_m, n_m from $\beta_m = \dot{\epsilon}_{ss} / \sigma_m(\infty)^{n_m}$

where $\dot{\epsilon}_{ss}$ is measured at multiple composite stresses



Initial Analysis of On-Axis Creep Behavior for Advanced 2D-Woven SiC/SiC Systems

Using limited tensile creep data at stresses below matrix cracking for the NASA Type -1 and Type -2 SiC/SiC, initial analyses shows the following **matrix** viscous creep parameters for $V_f \sim 0.2$:

	E_m	n_m	α_m (2400F)	β_m (2400F)	Matrix stress
Type - 1	180 GPA	1	2.0	$7.5 \times 10^{-12} \text{ MPA}^{-1}$	↓ with time
Type - 2	180 GPA	1	0.6	$2.7 \times 10^{-12} \text{ MPA}^{-1}$	↑ with time

Matrix parameters are consistent with similar monolithics and across CMC tensile creep data from 70 to 140 MPa and from 1200 to 1450°C

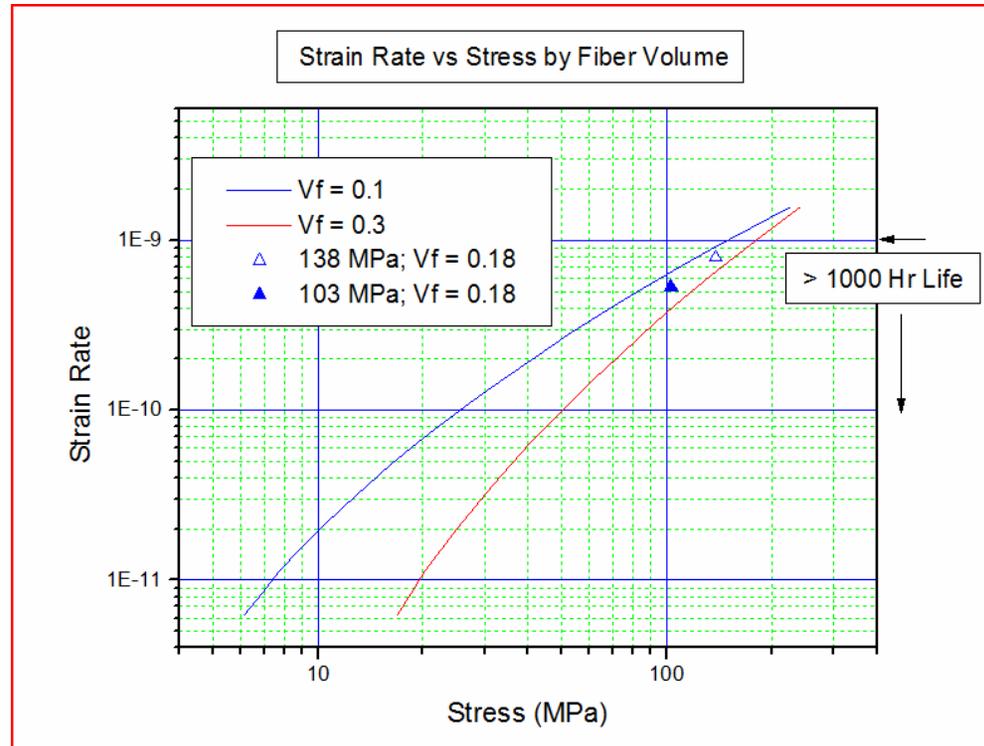
NASA Type-1 SiC/SiC tensile data with Si-containing SiC matrix indicate matrix creep > Sylramic-iBN fiber creep, also confirmed by increase in cracking strength after creep (Morscher and Pujar, JACS).

NASA Type-2 SiC/SiC tensile data with purier SiC matrix indicate matrix creep < Sylramic-iBN fiber creep *so that matrix is gaining stress during tensile creep.*****



Using Constituent Creep Parameters to Predict SiC/SiC Creep Rate and Rupture Life

Type-1 SiC/SiC at 2400°F (1315°C)



- With increasing composite stress, steady-state creep rate for Type-1 SiC/SiC should display a constantly decreasing stress exponent.
- Composite rupture life should be predictable from creep rate using Monkman-Grant Eq: $t_R = C / \dot{\epsilon}_{ss}^m$.



Summary and Conclusions

Current constituent–based modeling efforts are showing that

- **Based on measured tensile creep parameters for various fibers, simple analytical approaches can be applied to on-axis SiC/SiC creep curves to determine the effective tensile creep parameters for the complex matrix of advanced structural SiC/SiC composites.**
- **Initial analyses shows that these creep parameters can now be used for predicting a variety of key creep-related SiC/SiC properties such as time-dependent matrix stress, constituent creep and content effects on composite creep rates and rupture times, and internal stresses on fiber and matrix during and after composite creep.**
- **For NASA Type-1 SiC/SiC with Si in SiC matrix, initial analysis shows that stress on matrix will decrease or increase with time depending whether composite stress is tensile or compressive, respectively. For NASA Type-2 SiC/SiC with purer SiC matrix, opposite behavior is expected.**
- **For those SiC/SiC components with stress gradients (for example, due to thermal gradients), the stress history on the local matrix can be complex due to creep effects, and thus needs to be understood to predict component life.**



Planned Future Efforts

- To further enhance constituent-based creep modeling of advanced SiC/SiC composites, additional composite creep testing should be performed where
 - the applied composite stresses are reduced below 70 MPa
 - the test temperature is increased sufficiently to obtain steady-state creep behavior in a reasonable test time,
 - the stress directions are tensile, compressive, and off-axis
 - the composites are reinforced by 3D architectures
- Constituent-based models can then be used for composite lifing by developing creep-related rupture models for matrix and fiber
- Current analytical approaches for constituent modeling will be further improved by non-linear FE modeling to account for anisotropy, Poisson effects, off-axis behavior, non-2D architectures, and other physical mechanisms.
- Creep models will be used to further improve SiC/SiC high-temperature behavior by development of enhanced constituent materials, architectures, and creep-related composite fabrication processes.